Application of discrete element method for simulating feeding conditions and size reduction in cone crushers

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APPLICATION OF DISCRETE ELEMENT METHOD FOR SIMULATING FEEDING CONDITIONS AND SIZE REDUCTION IN CONE CRUSHERS

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ABSTRACT

The objective of this paper is to simulate the effects of segregation of the feed material entering the hopper on top of a typical cone crusher. The commercially available Discrete Element Method (DEM) software EDEM, provided by Dem solutions ltd, has been used to simulate and demonstrate some important aspects and phenomena and problems that are common in cone crushers. The first phenomenon of interest is segregation and uneven distribution of the feed entering a cone crusher. This is a common problem in many applications and leads to decreased comminution performance, poor product quality, uneven wear of the crusher manganese liners, high stress amplitudes and premature fatigue failures. This problem has been observed in many different applications and can sometimes severely affect the crusher performance in a negative way. A range of possible solutions to address the segregated feed is studied.

The internal size reduction process occurring in a cone crusher is also modelled an simulated by applying DEM. The results of the simulations show the dynamics of the crusher and the interaction of the rock material and the machine as well as the breakage and the size reduction process of the rock particles. The results from the DEM simulations of the crushing process are confirming earlier results retrieved by analytical models and simulations. The number of compressive crushing zones is confirmed to be around 10-11 in the studied crusher. The capacity of the crusher is controlled by the choke level. The two different breakage modes, inter and single particle, is clearly seen in the simulations. In addition, some new insights in the internal size reduction process are gained.

Keywords: cone crusher, DEM, segregation, feed, size reduction, particle size distributions

INTRODUCTION

Crushing and screening plants used for aggregates production and in mining industry consist of several different types of machine equipment and steelworks. Through the interaction with the equipment, the rock material is transformed from a blasted raw material to the final products. Rock products are particulate materials and the interaction with the production equipment is complex and not always easily analysed or understood by analytical methods.

In the aggregate and mining industry rock crushing and rock material handling are central parts of the production process. These systems are continuously improving and subjected to optimisation, analysis and development efforts. When conducting such work, many different parameters regarding machine and particle population has to be considered. Previously, analysis of bulk material flow had to be made by observing real systems and trying to directly or indirectly measure the parameters of interest. Though, there are a lot of cases where observation and measuring is very difficult to carry out, e.g. the flow behaviour inside a cone crusher or a vertical shaft impactor. There is also a need for evaluating machine design concepts in the development phase without building costly prototypes. The last year's improvement in DEM software now makes it useful as a practical and powerful tool in these situations.

The Discrete Element Method can be applied for simulation of the internal material flows and rock-machine interaction in crushing equipment. Due to the nature of the simulations additional information can be achieved in comparison to classical analytical techniques. Though, it is of

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outmost importance to have a fundamentally sound understanding of the equipment characteristics and performance in order to correctly set up the models and interpret the simulated results.

In comparison with other crushers and comminution equipment a relatively limited level of understanding is considered to be common knowledge about this crusher type. The results of the simulations demonstrate particle paths and velocity, compression ratios, contact forces, energy levels and particle size distributions. The fundamental understanding of the underlying reasons for miss-fed crushers is an important result of the simulations. The correlation between the DEM simulations and full-scale results is already on a level where it has proven its usefulness to solve problems occurring in industrial applications.

Several attempts have been made to model granular material and their interaction with machine elements using DEM. Cleary (2001) have conducted work on various kind of milling applications where e.g. power consumption, efficiency and milling mechanisms are investigated. Simulation and modelling of horizontal shaft (HSI) and vertical shaft impact (VSI) crushers have been done by (Schubert, 2005) and (Djordjevic *et al*, 2003). Both have used the bonded particle model (BPM) approach for modelling breakage. (Powell, 2008) proposed the Unified Comminution Model (UCM) as a general method for modelling comminution devices using DEM. The work is mainly aimed towards milling applications. Though, it is also possible to employ the model to other comminution devices where the particle breakage mainly happens by collision, as in VSI and HSI crushers. Lichter *et al* (2009) developed a DEM model based on a probability breakage model (PBM) for simulating cone crusher performance. Many researchers have also done work that is not of an application approach but instead targets the various aspects of DEM modelling. Kruggel-Emden *et al* (2008) have investigated the validity of a multi-sphere particle model by particle-wall impact trials. Investigations of the influence of a clustered particle models, as well as particle model development, have also been done by Latham (2008). Calibration of DEM parameters is a difficult area when it comes to DEM modelling. Coetzee (2009) have made progress by conducting various experiments in order to calibrate particle models and coefficients.

In this paper two different aspects of cone crusher applications are analysed by using the Discrete Element Method. The first part handles different aspects regarding how DEM can be used in the analysis of a problem area for aggregate material handling applications and a novel development process is proposed. A typical cone crusher feeding arrangement has been targeted for investigation and the novel development process has been applied when modelling and analysing the system. The second part of this paper is focused on the rock breakage and flow behaviour in a cone crusher by using a basic and simplified *Bonded Particle Model* (BPM). Here, the approach is of a more traditional character corresponding to that of research, not product development. The capacity and crushing behaviour is investigated and related to work done by Evertsson (2000) and Bengtsson (2009).

METHOD

Cone crusher feeding

Development and analysis process for bulk handling systems

When analysing a bulk material process system using DEM, a development process has to be established and utilised. The process described in Figure 1 is proposed as a development process for these kinds of applications. Without a method, finding an acceptable solution to a given problem will be far too time-consuming due to the nature of the problem and the large solution space.

The proposed method is based on general mechanical engineering problem solving processes described in e.g. (Lindstedt, 2003; Pahl, 1996; Savransky, 2000; Ullman, 2002) as well as the scientific approach described by Evertsson (2000). Though, due to the nature of DEM, some adaptations have to be made to these processes in order to efficiently utilise DEM as a tool. It should also be mentioned that the process is usable for both analysis and development of a redesign character as well as in the development phase of novel applications. The analysis and development done in this paper is of a redesign character. The presentation of the process is here done directly by applying it on a system and the aim is to verify the new process as well as contributing to new knowledge regarding feeding and segregation problems.

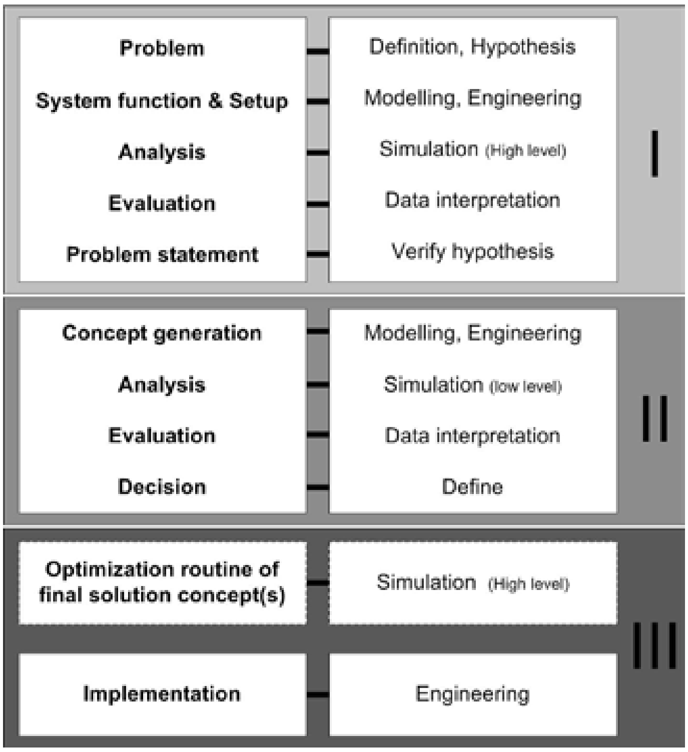

FIG 1 - The proposed DEM analysis and development process for bulk handling systems.

Stage I

The first phase of the process is aimed towards thoroughly investigating the existing system through 5 sub-steps. Here the emphasis lies on thoroughly penetrating the present problem by initially stating a problem definition based on observations and generate an initial hypothesis regarding the causes of the problem. Further, the system geometry is modelled and all data regarding mechanical, dynamical and particle population properties are gathered. This sub-step requires a high degree of know-how, both about the specific engineering field and the studied system. Also, either CAD-modelling resources or existing CAD-geometry has to be available if the geometry is not very elementary and can be created in the DEM software with e.g. boxes, circles and planes.

DEM models can be defined in a vast number of ways with different level of complexity and conformation to reality. Hence, it is of importance to define what level a certain analysis needs due to the relation between complexity, simulation time, precision and cost. The complexity level in the first phase should be relatively high as the purpose of the analysis is to give as fundamental understanding as possible regarding problem areas in the interaction between particle and machine.

The system subjected for analysis in this work is a typical feeding process of a cone crusher. The process consists of four elements main elements; conveyor A, chute, conveyor B and a cone crusher, see Figure 2. The initial hypothesis regarding the system, prior to any simulations is that a segregation effect is present in each element and that these segregation effects are coupled. In order to verify this hypothesis a DEM model is created with a high level of detail regarding particle population properties.

The shape of the particles in a DEM model is highly influential on the overall quality and validity of the model (Kruggel-Emden *et al*, 2008; Latham, 2008; Price, 2007). The particle population is modelled by using a set of clustered spheres created in the software ASG (Cogency, 2009). These clusters consists of five sub-spheres which are placed and sized in order to as good as possible resemble 3D representation of real scanned rock particles. It is possible to use more sub-spheres in order to enhance the simulation quality. Though, the number of spheres also drives simulation time hence it is a trade-off between quality, number of cluster-particles and simulation time. The particle population is created by six different cluster-particle types with different shapes ranging from cubical to relatively flaky. These are then divided into two groups with different particle size distributions modelled by normal distributions, creating the overall particle size distribution.

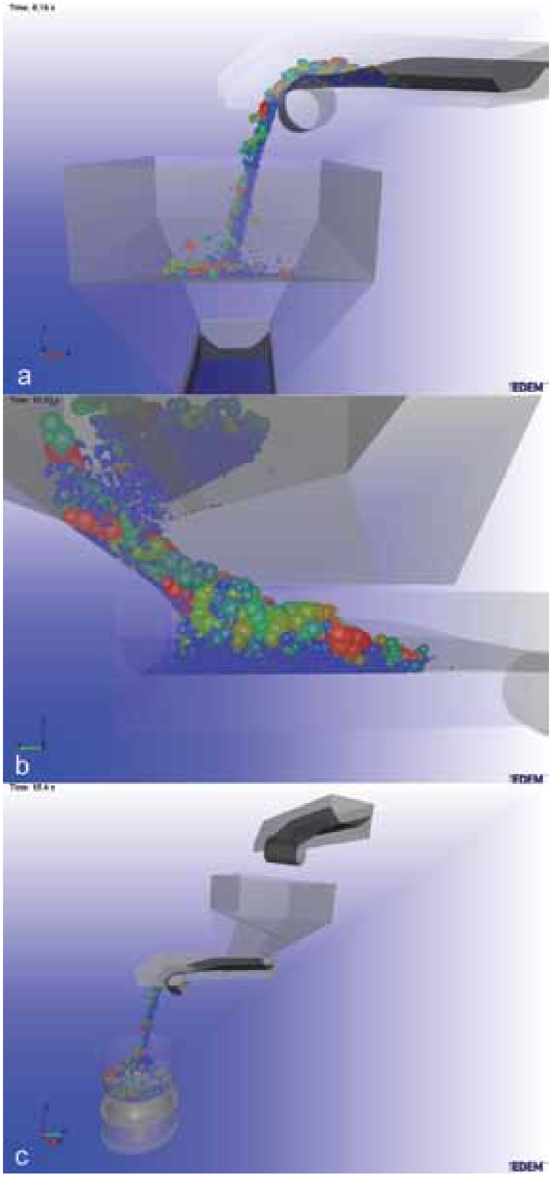

FIG 2 - Simulation of material flow through the investigated cone crusher feeding application (Stage I in the analysis process). Particles are coloured by mass from blue to red where blue corresponds to the lower spectrum and red to the higher. a) Conveyor A to Chute, b) Chute to Conveyor B, c) Conveyor B to Cone Crusher.

As mentioned earlier the particle flow behaviour is highly influenced by the material coefficients and material-material interaction properties. Several authors have conducted work aimed at least partly towards optimising these coefficients for various materials and applications (Cleary, 2001; Coetzee, 2009). Even though this is a crucial part of DEM methodology this paper is not aimed towards fully exploring this field. Simple particle slump tests have been conducted in order to capture the approximate coefficients of a granite material. A steel pipe is filled with a mono sized fraction and is lifted at constant velocity. This is repeated ten times and the angle of repose and spread is recorded. The same system is then modelled in EDEM and the coefficients are varied until satisfactory results are achieved.

Stage II

Four different concepts are developed and modelled as solutions to the segregation and miss feeding problem. In order to evaluate the performance and ability of each concept a simulation set on a low level is conducted. The particle population is simplified into two sizes, large particles ($D_{large} = 200mm$) and small particles ($D_{small} = 70mm$). The lower resolution simulation is chosen in order to be able to perform evaluating simulations quickly and in an iterative manner. This is very important since the developer in this stage mostly is interested in the overall trends and a general performance of the concepts. The concepts and snapshots from the simulations are seen in Figure 3.

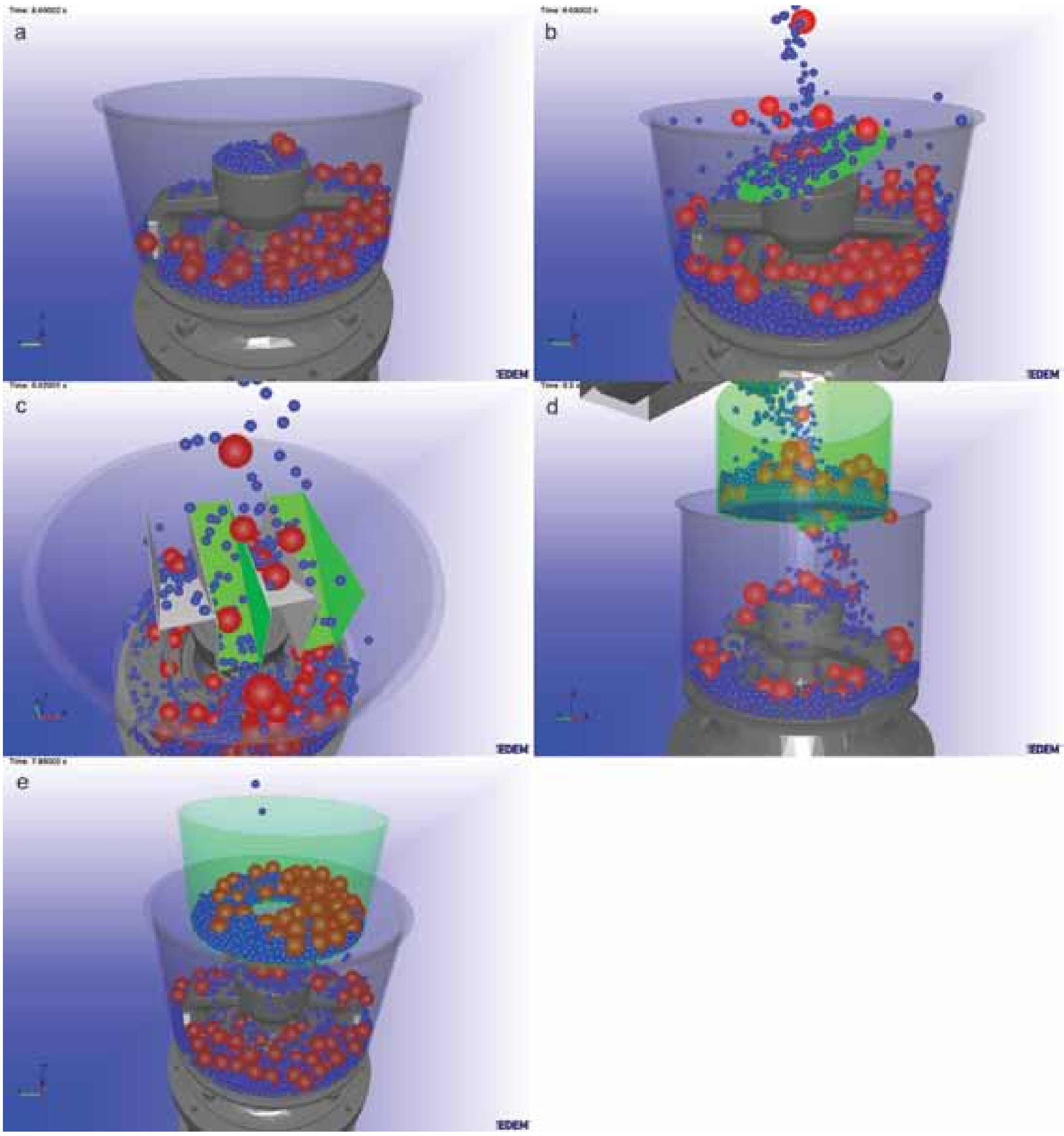

FIG 3 - Generated concepts, from top left: a) No randomiser b) Rotating disk c) Splitter d) Eccentric rotating hopper e) Hopper.

Modelling and simulation of the size reduction process in a cone crusher

The crushing operation of cone crushers is discrete and repeated. This fact makes modelling and simulation challenging as errors of any kind in the different crushing steps occurring in the crushing cavity will cumulate. Of this reason the simulations must be carefully examined before any conclusions can be drawn.

The studied crusher in this work is a Sandvik CH 430 crusher equipped with a fine crushing chamber (F). The Sandvik CH430 cone crusher was previously named Svedala H3000/H3800 and was originally developed from the well renowned Allis-Chalmers 36” Hydrocone. The closed side setting (CSS) is 12 mm and the eccentric throw is selected to be 48 mm. The eccentric speed of the crusher is 360 rpm or 6 Hz. Due to the computational intensive character of DEM, it is necessary to always consider if it is possible to make use of a geometrical symmetry or uniformly behaviour in some direction of the studied system. In order to reduce the calculation time, a section of the crusher and the crushing chamber was filled with rock particles. This section has a width of 36°.

The selected crusher type and crushing chamber is exactly the same as the studied cone crusher in the thesis presented by Evertsson (2000). Therefore, extensive test data for the crusher performance are available for the evaluation.

Bonded particle model (BPM)

The basic principle of a bonded particle model is that a cluster of sub-particles are bonded together according to certain strength characteristics. When the stress on a sub-particle and its bonding exceeds a specified threshold value, the bond will break and fragmentation occurs. Post the fracture event the particles will act as hard spheres with further interaction controlled by the default *Hertz-Mindlin contact model*. The BPM model in this paper is based on the bonding of 127 sub-particles (d = 6mm) bonded together, forming a larger sphere (D = 40mm). The particles are created using a customised particles replacement factory provided by EDEM. Initially 100 'dummy' particles are created and at a given time step each 'dummy' particle is replaced by 127 sub-particles, each with a specific location described by a cluster coordinate text-file. When the replacement has been performed the sub-particles are bonded together using the *Hertz-Mindlin with bonding* physics model in EDEM (Table 1).

TABLE 1

Bonding parameters for the BPM model.

Bonding parameter	Numerical value	
Normal stiffness	5e+10	[N/m]
Shear stiffness	1e+10	[N/m]
Critical normal stress	1e+07	[Pa]
Critical shear stress	5e+06	[Pa]
Bonded disk radius	5	[mm]

RESULTS

In this section the result of performed simulations will be presented. First the outcome of stage I and stage II from the analysis of the cone crushers feeding application using the proposed process will be shown. The third stage, optimisation and implementation, will not be handled in this paper. Further, the results of the DEM analysis of breakage and size reduction will be presented.

Cone crusher feeding

Stage I

When particles move on a conveyor belt the particle population experiences a strong segregation effect. The smaller particles transmigrate between the larger particles to the bottom of the particle bed and the larger particles are due to vibrations lifted to the top, see Figure 2b. When the particle flow is leaving the conveyor the segregation leads to segregation in the next coming fed element. The effect of segregation can thereby increase for every element the particle population flows through. In this case the segregation in z-direction on conveyor A will lead to segregation effects in the x-direction in the chute, see Figure 4. Further, when releasing the material on conveyor B the segregation effect in the x-direction is to some degree transmitted, see Figure 2b. Though, the major part of the segregation effect on conveyor B is acting in the z-direction, see Figure 4b. The final particle position distribution in the crusher is showed in Figure 4c. The plot clearly shows both segregation and a miss-feeding effect. The main causes are the segregation conditions from the belt resulting in a segregation in the feeding, the flow velocity when hitting the spider cap of the crusher and the impact angle. The maximum flow velocity in the simulation is 9.6 m/s and the impact angle is ~76°.

Stage II

The simulation results for the original feed hopper arrangement together with four alternative feed arrangement concepts are shown in Figure 5 a-f. In these figures a horizontal cross-section of the feed hopper is depicted in which the densities of small and large particles are shown. In Figure 5a the simulation results shows a clear and heavily segregation with a high density of large particles in the lower part of the feed hopper.

In Figure 5b the result for a rotating disc distributor is shown. The result is better than the original design but due to the angle of impact of the feed material there is still a clear segregation with larger particles in the lower part of the feed hopper.

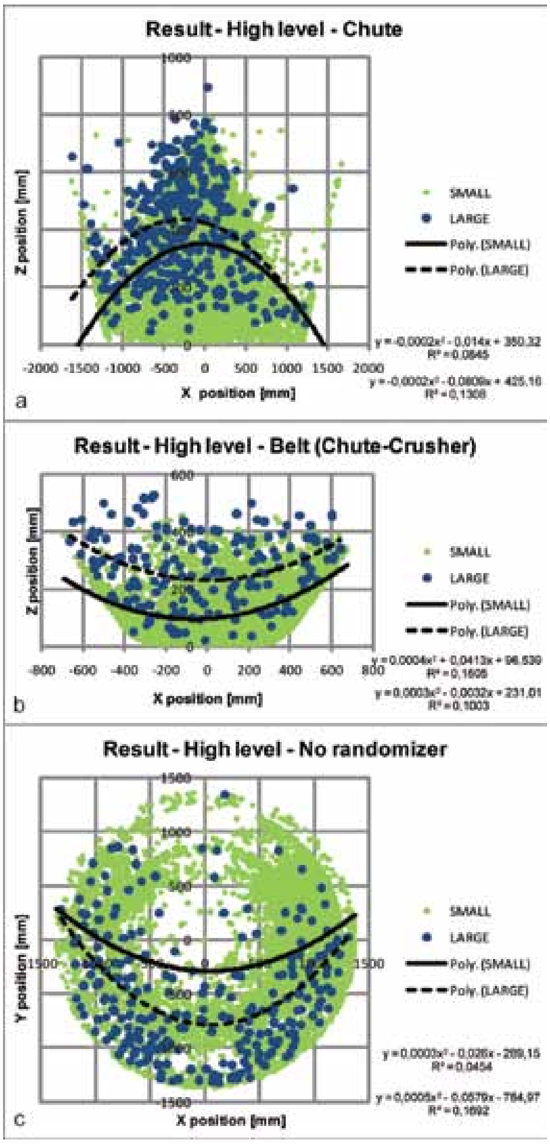

FIG 4 - Density distribution (high level simulation in stage I), from top, a) The chute, projected on the XZ-plane. b) Conveyor B, projected on the XZ-plane. c) The crusher, projected on the XY-plane.

In Figure 5c the result for a splitter is shown. The result is symmetric around the x-axis but there is very little material under the actual splitter arrangement.

In Figure 5d the result for a rotating hopper with an eccentric outlet is shown. The result is fairly good.

In Figure 5e the result from simulations of a "double" feed hopper arrangement is shown. This is definitely the best result with the smallest segregation. It is interesting that the final result is the best even due to the fact that the segregation in the upper part of the feed hopper arrangement is severe as shown in Figure 5f.

The size reduction process in a cone crusher

Just by observing the animated results from the DEM simulations a number of qualitatively valuable observations can be made. In particular, some of the main conclusions in the thesis presented by Evertsson (2000) are of interest. Snapshots taken from the DEM simulations of the CH430 cone crusher are shown in Figure 6. To start with, the number of crushing compressions (crushing zones) in the DEM simulation is around 10 to 11. It is clearly seen that the particles are falling freely when the mantle is in the opening phase. The mechanism driving the material transport, and thus capacity, between the crushing events is therefore free fall as stated and concluded earlier. To some extend the crushing action in the chamber is a little bit stochastic. This is a new observation which can be indirectly seen in a starved or trickle fed crusher by observing the particle motion in the very inlet of the crushing chamber.

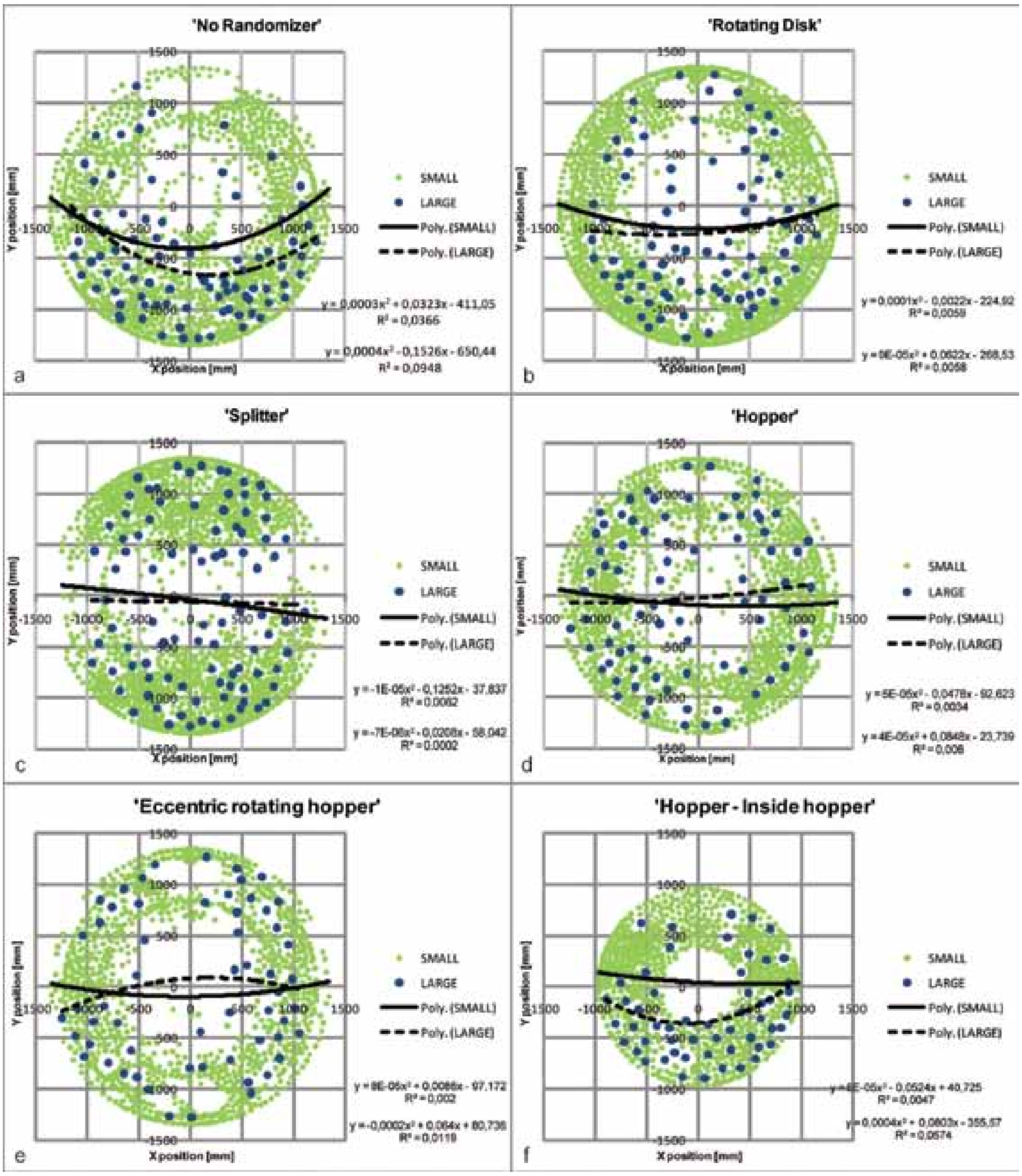

FIG 5 - Density distributions (low level simulation in stage II), from top left. a) No randomiser, b) Rotating disk, c) Splitter, d) Eccentric Rotating Hopper, e) Hopper, f) Density distribution in the hopper.

The particles are queuing and the average velocity down the chamber is restricted by particles in front. This supports the conclusion that capacity is controlled at the choke level where the bulk density of the rock material is the highest. The major part of the crushing for the studied feed material seems to occur around the choke level and relatively high up in the crushing chamber. This observation supports the theory about breakage modes. Interparticle breakage is dominating above the choke level and single particle breakage below. Below the choke level the top-size is calibrated. No forming of particle bridges, and therefore no interparticle breakage, can be observed below the choke level. Below the choke level, particles smaller than the distance between the mantle and concave are falling down the chamber without any further crushing. This is detrimental to particle shape in aggregate production. This supports the conclusions drawn by Bengtsson (2009)

The simulated capacity does not fully correspond to measured capacity due to several reasons. First of all the simulated rock particles are built up by 127 spherical sub-particles and the maximum packing degree of spherical mono sized particles is 0.74. The particle packing of the BPM in this simulation is roughly 0.43. Therefore, the simulated capacity should be considered as higher than results indicate, see Figure 7. Though, in order to achieve the correct capacity, it is not as easy as dividing the simulated capacity with the packing factor of the particles since it changes when a

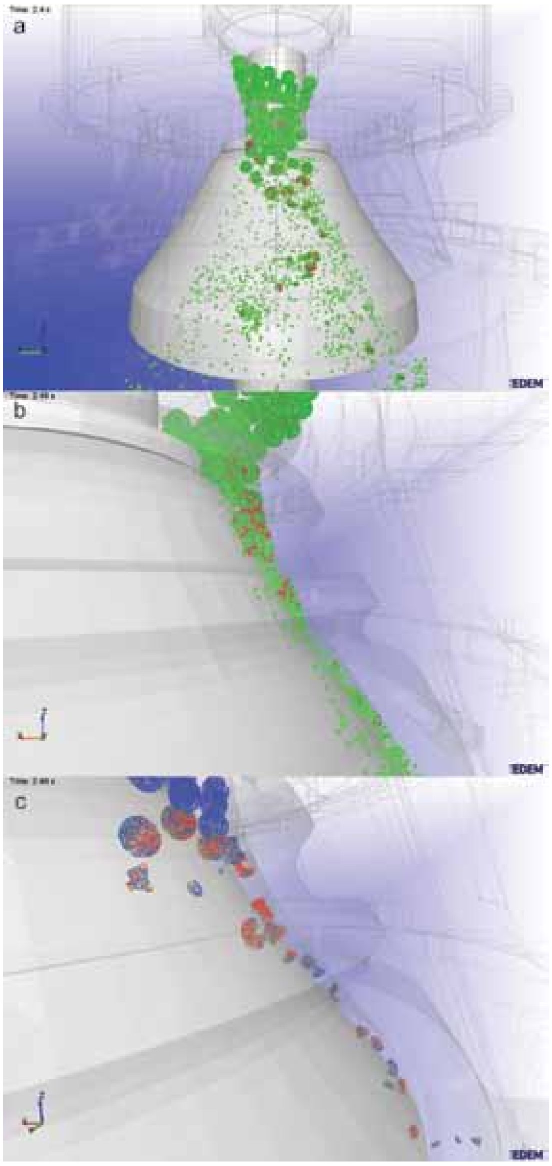

FIG 6 - Snapshot from DEM simulation of breakage in a CH430 cone crusher.

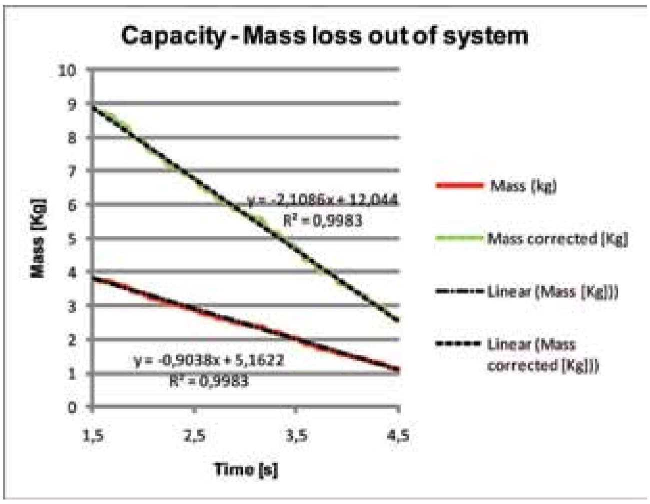

FIG 7 - Mass loss out of the system domain corresponding to the capacity of the simulated crusher segment.

particle is fragmented in smaller clusters. These sub-clusters will be subjected to compression in the next coming crushing event and hence also influence the total capacity. If we, even so, make the assumption that the capacity is restricted at its most at the choking zone, where particles mainly are crushed, then later fragmentations can be at least partly disregarded with respect to influencing the capacity. This leads to roughly a factor two of the simulated capacity. The simulated capacity is then 72 tph. The fact that both the bonded particles and its fractions are spherical also influences the flow behaviour in the top zone. A higher degree of lifting effect is experienced than would be normal with angular non-spherical particles.

CONCLUSION

Segregation of material in different positions of a material handling and feeding system has been successfully simulated. Segregation in these types of situations seems to occur immediately when the material is moved on conveyors, through chutes and in bins. When the segregated material then is feed to a cone crusher the result is an uneven distribution of the particle size around the feed hopper on top of the crusher. This uneven distribution is detrimental to the crusher operation and performance.

A number of different concepts for mixing the particle size distributions have been studied. The best solution of the studied concepts is the one where the material first enters a smaller chute and then is redirected down to the spider cap of the crusher. The proposed DEM analysis and development process for granular material handling systems have been used. The process is efficient and utilises DEM as a powerful tool by varying the resolution and quality of the simulations with respect to the needs of the engineer or researcher in different development and evaluation stages.

The DEM simulation of the size reduction process in the crushing chamber of a cone crusher supports several of the conclusions presented in earlier work. The simulation results are very promising on a qualitative level. Therefore, future work will be focused in this area in order to increase the quantitative precision of the simulations. The DEM simulation technique will be used for analysing and optimising the geometry of the crusher inlet and the crushing chamber geometry.

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